THE EARTHQUAKE AT CHARLESTON IN 1886

G. A. BOLLINGER

At about 9:50 p.m. on August 31, 1886, a large earthquake occurred in Charleston, South Carolina. Its magnitude (M_s) has been estimated at 7.5, its modified Mercalli intensity (MMI) was X, and it was sensibly felt by people over an area of some 2 million square miles. There was extensive damage to the city of Charleston ($5 million in 1886 dollars) and death estimates ranged between 60 and 100 (1886 population density). In Milwaukee, Wisconsin, large buildings were shaken violently, windows were broken, and people fled into the streets. At Brooklyn, New York, buildings were also shaken to the extent that people were frightened; chandeliers rattled. On the sixth floor of a Chicago hotel, plastering was thrown from ceilings and guests were nauseated and fled the hotel in terror. The shock was felt as far away as Boston, Massachusetts; Bermuda; and Cuba.

The 1886 earthquake was certainly the largest known for the southeastern United States and one of the largest historic earthquakes in all of eastern North America. The following will first discuss three important factors that can be derived from consideration of the 1886 shock in the context of the historical seismicity of the region. Each of those factors then will be seen to have one or more important, associated questions. Finally, the physical effects from this large earthquake will be presented in some detail.

IMPORTANT FACTORS AND ASSOCIATED QUESTIONS

The important factors are:

1. The fact that a magnitude 7.5 earthquake occurred in Charleston, South Carolina, demonstrates the presence in the area of a seismogenic structure capable of generating such a shock. In principle, such a structure could occur elsewhere, but at the present time Charleston is the only locale in the Southeast that has its presence confirmed.

2. The earthquake activity in the eastern United States was at a much higher level prior to the turn of the century than it has been subsequently. In addition to the 1886 shock, there was a

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magnitude 5.7 (M_S) earthquake located in western Virginia in 1897 and a series of magnitude 8-8+ earthquakes in southern Missouri during 1811-1812. None of those three states, South Carolina, Virginia or Missouri, or their neighboring states has experienced such large shocks during the twentieth century. Thus, we have documentation that the level of earthquake energy release in the region can change with time.

3. The decrease of earthquake vibrations with increasing distance from an earthquake epicenter in the eastern United States has been shown by numerous studies during the past decade to be very slow, especially with respect to the western part of the country. What this means is that larger areas of structural damage and other earthquake effects can be expected in the East than in the West. The 1886 Charleston earthquake is a good example of those larger than average affected areas.

Some direct questions that follow from the above factors are:

1. Is the Charleston area the only area in the region capable of generating a 7.5 magnitude earthquake? The answer is that it probably is not since it is geologically reasonable for other such seismogenic structures to be present. Also, there are zones of persistent, low-level earthquake activity in the eastern United States. Those zones are candidates for larger shocks in the future.

2. Although the seismicity of the region is currently at a low level, is it going to continue that quiescence or are we in a lull before another period of increased earthquake occurrences?

3. Can the 1886 Charleston earthquake be used as a "type example" of what to expect from a future occurrence of a large earthquake in the region? Yes, but the soil and bedrock geology are certainly different in the Appalachian highlands (Valley and Ridge and Blue Ridge provinces) than in the Atlantic Coastal area that was host to the 1886 shock. These differences as well as the difference in construction practices and materials between 1886 and 1985 need to be taken into account. The differences in type and degree of land utilization also are relevant.

The preceding questions cannot be answered in a deterministic fashion. We just do not have enough data of all kinds--geologic, geophysical, seismological, and engineering--to develop precise answers. What can be done, however, is to approach the problem from a probabilistic point of view. The U.S. Geological Survey (USGS) has been very active in such studies for the past decade. (For summary a overview of the USGS results see the paper by Walter W. Hays.)

DESCRIPTION OF THE EFFECTS FROM THE 1886 EARTHQUAKE

Epicentral Region

At least 80 kilometers of railroad track was seriously damaged and more than 1,300 km^2 of extensive cratering and fissuring occurred as a result of the 1886 earthquake. In Charleston, the railroad-track damage and cratering were virtually absent, but many buildings on both good and poor ("made") ground were destroyed. Specifically, Dutton (1889) reports:

> There was not a building in the city which had wholly escaped injury, and very few had escaped serious injury. The extent of the damage varied greatly, ranging from total demolition down to the loss of chimney tops and the dislodgement of more or less plastering. The number of buildings that were completely demolished and leveled to the ground was not great. But there were several hundred which lost a large portion of their walls. There were very many also which remained standing, but were so badly shattered that public safety required that they be pulled down altogether. There were not, so far as is at present known, a brick or stone building which was not more or less cracked, and in most of them the cracks were a permanent disfigurement and a source of danger or inconvenience. A majority of them, however, were susceptible to repair by means of long bolts and tie-rods.

Also see the reprint of USGS Professional Paper 1028 (1977) that concludes this paper.

At a Distance of 100 Kilometers (60 miles)

Most severely affected at this range from the epicenter of the 1886 shock were coastal locations such as Port Royal and Beaufort to the southwest and Georgetown to the northeast. At Port Royal (MMI of IX), the shock was described by the United Press as "very violent." Houses were moved on their foundations and people were thrown to the ground. At Beaufort (Associated Press) and Georgetown (Dr. M. S. Iseman, M.D.), both with an MMI of VIII, chimneys and chimney tops were thrown down, brick parapets were dislodged, and brick buildings "undulated." Residents fled their houses and remained in the streets and fields all night, many praying. At Beaufort, the Charleston Yearbook described the shock as "very severe," lasting 30 seconds, cracking some large buildings, and causing a 2-foot depression over an area some 60 feet in circumference.

Noncoastal location such as Manning to the north and Orangeburg and Bamberg to the northwest were shaken at a MMI level of VII. All reported damage to brick houses and brick walls and the falling of plaster. The response of the populace at these northerly sites was also one of terror and many camped in the open air overnight.

At a Distance of 200 Kilometers (120 miles)

Reports from Augusta, Georgia, 200 kilometers from the epicenter, deal extensively with the response of the citizenry. The Savannah Morning News of September 2, 1886, gave a September 1 communication from Augusta citing: "...two ladies lie at the point of death from fright," "...an old lady died from fright," and "many ladies fainted and thousands of men were completely unnerved. The citizens remained in the streets all night."

The following paragraphs from Dutton (1889) comment on the pronounced psychological effects at Augusta as well as the structural damages suffered there:

> Thus Augusta, in Georgia, just beyond the 100-mile circle, was shaken with great violence. Many buildings were seriously damaged. At the arsenal two heavy walled buildings used as officer's quarters were so badly shattered that reconstruction was necessary. Many cornices were dislodged and it is estimated that more than a thousand chimneys were overthrown. People residing in brick dwellings refused for several days to enter them and found lodgings in wooden houses or camped in the streets and gardens. So great was the alarm felt that business and society were for two days fully paralyzed as in Charleston. Everyone was in a state of apprehension that the worst was yet to come and the only thing to be thought of was safety. Indeed, among all the large cities of the South, the general tenor of the reports indicates that Augusta stands next to Charleston in respect to the degree of violence of the shocks and the consternation of the people.
>
> Augusta is built in close proximity to the contact of the new and older strata, and starting from that city it will be of interest to follow this line of contact northeastward. In detail the course is more or less sinuous. A few miles to the northeast of Augusta is a little railway station named Langley, where a small tributary of the Savannah River has been dammed to secure water power. The ground in this neighborhood, which is a loose soil thinly covering harder rocks below, was in many places fissured by the earthquake and opened in many cracks, some of which were several inches in width. A number of large cracks passed through the dam, opening passage for the water in the reservoir, which quickly enlarged the fissures. The county below was quickly aflood. The railway track was swept [away], and before warning could be given a passenger train ran into the flood and upon the broken track, where it was wrecked, with some loss of life. In this neighborhood the towns of Bath, Graniteville, and Vaucluse, which stand upon outcrops of crystalline rocks, report shocks of very great severity. Still farther to the northeastward, Batesburg, Leesville, and Lexington give similar reports. Passing beyond Columbia along the same line of contact, we find reports of very violent shocks at Blythwood, Camden, Chesterfield, and Cheeraw.

The Savannah Morning News report also noted that "the most severe damage was done on the Sand Hills in Georgia and in Aiken County, South Carolina." Specific localities mentioned were Langley and Bath, just across the Savannah River from Augusta, some 10 kilometers to the east. At Langley, on the South Carolina Railroad, 24 kilometers (15 miles) from Augusta, Georgia, and 200 kilometers (125 miles) from Charleston, "the earthquake destroyed the mill dam and the water washed away the roadbed. A train dashed into the flood, and the engineer and fireman were drowned. The engine is now 40 feet under water." Dutton (1889) reported: "Houses badly shaken and glasses broken; dams broke loose destroying 1,000 feet of railroad; terrible suffering among the inhabitants." An MMI of X is assigned to the Langley, South Carolina, locale (Bollinger and Stover, 1975).

At a Distance of 400 Kilometers (240 miles)

At an epicentral distance of 400 kilometers, the level of ground-shaking continued to cause panic among the people: "a state of terror and excitement; people left their houses and many stayed in the streets all night (Beaufort, North Carolina); "streets rapidly filled with people, screams of frightened persons could be heard" (Raleigh, North Carolina); "rushed frightened from their houses into the streets; terror-stricken men, women and children, in night dress, crowded the streets in a moment; a number of ladies fainted" (Ashville, North Carolina); and "people rushed into the streets in indescribable confusion, each looking for an explanation from the others; the streets at 10 o'clock are full of people, who fear to return to their houses" (Atlanta, Georgia).

Buildings and household items (mirrors, pictures, lamps, dishes, window glass, etc.) were shaken at a MMI level of VIII or less. Atlanta, in northern Georgia, reported one house (Marrietta Street) "shaken to pieces," all the chimneys fell from the six-story Construction building in the city, window glass was broken, chimneys were knocked down, and dishes and glasses were smashed to pieces. However, Valdosta, to the south-southeast and near the Georgia-Florida border, reported only falling of plaster (MMI VI).

Across the entire state of North Carolina, MMI effects ranged from V to VII. Examples of the highest levels were seen at Beaufort on the coast, Raleigh in central North Carolina and Waynesville in the extreme southwestern part of the state. The seismic waves at those locations caused chimneys to be overthrown or have their tops shaken off, some walls to crack, plastering to be thrown down, buildings to rock, and some floors to break "loose from their supports." Additionally, church bells were rung, clocks stopped, mirrors and pictures were thrown from walls, and lamps were overturned. At Asheville, North Carolina, houses were violently shaken, but no buildings were "shaken down" (MMI of VI). In Black Mountain (20 kilometers to the east of Asheville), the vibrations were accompanied by loud explosive sounds and heavy rumblings, and large masses of rock were dislodged from several steep slopes and rolled into the valleys below.

THROUGHOUT THE COUNTRY

The following pages are a reprint of a study of the effects of the 1886 earthquake throughout the United States that was published in 1977 as part of Studies Related to the Charleston, South Carolina, Earthquake of 1886--A Preliminary Report, USGS Professional Paper 1028, edited by Douglas W. Rankin (Washington, D.C.: U.S. Government Printing Office).

Reinterpretation of the Intensity Data for the 1886 Charleston, South Carolina, Earthquake

By G. A. BOLLINGER

STUDIES RELATED TO THE CHARLESTON, SOUTH CAROLINA, EARTHQUAKE OF 1886—A PRELIMINARY REPORT

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1028-B

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REINTERPRETATION OF THE INTENSITY DATA FOR THE 1886 CHARLESTON, SOUTH CAROLINA, EARTHQUAKE

By G. A. Bollinger [1]

ABSTRACT

In 1889, C. E. Dutton published all his basic intensity data for the 1886 Charleston, S.C., shock but did not list what intensity values he assigned to each report, nor did he show the distribution of the locations of these data reports on his isoseismal map. The writer and two other seismologists have each independently evaluated Dutton's 1,300 intensity reports (at least two of the three interpreters agreed on intensity values for 90 percent of the reports), and the consensus values were plotted and contoured. One map was prepared on which contours emphasized the broad regional pattern of effects (with results similar to Dutton's); another map was contoured to depict the more localized variations of intensity. As expected, the latter map shows considerable detail in the epicentral region as well as in the far-field. In particular, intensity VI (Modified Mercalli (MM)) effects are noted as far away as central Alabama and the Illinois-Kentucky-Tennessee border area. Dutton's "low intensity zone" in West Virginia appears on both isoseismal maps.

A maximum MM intensity of X for the epicentral region and IX for Charleston appears to be appropriate. Epicentral effects included at least 80 km of railroad track seriously damaged and more than 1,300 km ^{2} of extensive cratering and fissuring. In Charleston, the railroad-track damage and cratering were virtually absent, whereas many, but not most, buildings on both good and poor ground were destroyed.

The epicentral distances to some 800 intensity-observation localities were measured, and the resulting data set was analyzed by least-square regression procedures. The attenuation equation derived is similar to others published for different parts of the eastern half of the United States. The technique of using intensity-distance pairs rather than isoseismal maps has the advantages, however, of completely bypassing the subjective contouring step in the data handling and of being able to specify the particular fractile of the intensity data to be considered.

When one uses intensities in the VI to X range, and their associated epicentral distances for this earthquake, body-wave magnitude estimates of 6.8 (Central United States intensity-velocity data published by Nuttli in 1976) and 7.1 (Western United States intensity-velocity data published by Trifunac and Brady in 1975) are obtained.

INTRODUCTION

The problems associated with the description of seismic ground motion in a minor seismicity area such as the Southeastern United States are well known. In that region, the largest events took place before instruments were available to record them, so that only qualitative descriptions of their effects exist. During the past few decades, when instruments began to be used, no event having $m_b>5$ has taken place. Thus we have quantitative data only for small events, and we need to analyze the qualitative data, which are all that is available for larger events.

The purpose of this study is to review thoroughly the data that do exist and to derive as much information as possible concerning regional seismic ground motions. Fortunately, the largest earthquake known to have occurred in the region, the 1886 Charleston, S.C., earthquake, was well studied by Dutton (1889) and his coworkers. An excellent suite of intensity information is thus available for that important earthquake. Secondly, the Worldwide Standard Seismograph Network (WWSSN) stations in the Eastern United States provide data on the radiation from the regional earthquakes that have occurred since installation of the stations. Finally, intensity-particle-velocity relationships as well as attenuation values for various seismic phases have been proposed that can be utilized in an attempt to synthesize the above data types.

The initial part of this paper is concerned with a reevaluation of the intensity data for the 1886 Charleston earthquake, and the second part, with a consideration of the attenuation of intensity as distance from the epicenter increases. (The distance

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from the epicenter is hereafter called epicentral distance.) The concluding section presents a magnitude estimate for the 1886 shock.

This research was conducted while the author was on study-research leave with the U.S. Geological Survey (U.S.G.S.) in Golden, Colo. Thanks are extended to the members of the Survey, particularly Robin McGuire and David Perkins, for their many helpful discussions. Robin McGuire did the regression analysis presented in this paper, and Carl Stover provided a plot program for the intensity data. Thanks are also due to Rutlage Brazee (National Oceanographic and Atmospheric Administration, N.O.A.A.) and Ruth Simon (U.S.G.S.) for interpreting the sizable amount of intensity data involved in this study.

This research was sponsored in part by the National Science Foundation under grant No. DES 75-14691.

INTENSITY EFFECTS IN THE EPICENTRAL REGION

Dutton assigned an intensity X as the maximum epicentral intensity for the 1886 shock. He used the Rossi-Forel scale; conversion to the Modified Mercalli (MM) scale results in a X–XII value. However, the revised edition (through 1970) of the "Earthquake History of the United States" (U.S. Environmental Data Service, 1973) downgraded Dutton's value to a IX–X (MM). Because of this revision, it is appropriate to compare the scale differences between these two intensity levels (IX and X) with the meizoseismal effects as presented by Dutton.

Ground effects, such as cracks and fissures, and damage to structures increase from the intensity IX to the intensity X level, whereas damage to rails is first listed in the MM scale at the X level. Taken literally, rail damage is indicative of at least intensity-X-level shaking. Richter (1958, p. 138) also listed "Rails bent slightly" for the first time at intensity X. However, he instructed (p. 136) that, "Each effect is named at that level of intensity at which it first appears frequently and characteristically. Each effect may be found less strongly, or in fewer instances, at the next lower grade of intensity; more strongly or more often at the next higher grade." Thus, widespread damage to rails is a firm indicator of intensity-X shaking.

In discussing building damage, it is convenient to use Richter's (1958, p. 136–137) masonry A, B, C, D classification:

Masonry A. Good workmanship, mortar, and design: reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.

Masonry B. Good workmanship and mortar: reinforced, but not designed in detail to resist lateral forces.

Masonry C. Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.

Masonry D. Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

At the IX level, masonry D structures are destroyed, masonry C structures are heavily damaged, sometimes completely collapsed, and masonry B structures are seriously damaged. Frame structures, if not bolted, are shifted off their foundations and have their frames racked at IX-level shaking, whereas at intensity X most such structures are destroyed. Nearly complete destruction of buildings up to and including those in the masonry B class is a characteristic of the intensity-X level.

Only in Charleston do we have a valid sample of the range of structural damage caused by the 1886 earthquake. It was the only nearby large city, and it contained structural classes up to the range between masonry C and masonry B. Many of the important public buildings, as well as mansions and churches, had thick walls of rough handmade bricks joined with an especially strong oyster-shell-lime mortar. The workmanship was described as excellent, but nowhere in Dutton's (1889) account is reference made to special reinforcement or design to resist lateral forces. Structures outside the Charleston area (as in Summerville, see p. 21) were built on piers, some 1–2 m (3–6 ft) high, thereby making the structures inverted pendulums. Dutton's report for Charleston indicates that although the damage was indeed extensive (see below), most masonry buildings and frame structures were not destroyed. This fact plus Dutton's report on the absence of rail damage and extensive ground effects in the Charleston area indicates an intensity level of IX.

The following quotations from Dutton's report (1889, p. 248–249, 253) contain detailed descriptions of the structural damage in Charleston caused by the earthquake of 1886:

> There was not a building in the city which had wholly escaped injury, and very few had escaped serious injury. The extent of the damage varied greatly, ranging from total demolition down to the loss of chimney tops and the dislodgment of more or less plastering. The number of buildings which were completely demolished and leveled to the ground was not great. But there were several hundred which lost a large portion of their walls. There were very many also which remained standing, but so badly shattered

that public safety required that they should be pulled down altogether. There was not, so far as at present known, a brick or stone building which was not more or less cracked, and in most of them the cracks were a permanent disfigurement and a source of danger or inconvenience. A majority of them however were susceptible of repair by means of long bolts and tie-rods. But though the buildings might be made habitable and safe against any stresses that houses are liable to except fire and earthquake, the cracked walls, warped floors, distorted foundations, and patched plaster and stucco must remain as long as the buildings stand permanent eye-sores and sources of inconveniences. As soon as measures were taken to repair damages the amount of injury disclosed was greater than had at first appeared. Innumerable cracks which had before been unnoticed made their appearance. The bricks had "worked" in the embedding mortar and the mortar was disintegrated. The foundations were found to be badly shaken and their solidity was greatly impaired. Many buildings had suffered horizontal displacement; vertical supports were out of plumb; floors out of level; joints parted in the wood work; beams and joists badly wrenched and in some cases dislodged from their sockets. The wooden buildings in the northern part of the city usually exhibited externally few signs of the shaking they received except the loss of chimney tops. Some of them had been horizontally moved upon their brick foundations, but none were overthrown. Within these houses the injuries were of the same general nature as within those of brick, though upon the whole not quite so severe.

The amount of injury varied much in different sections of the city from causes which seem to be attributable to the varying nature of the ground. The peninsula included between the Cooper and Ashley Rivers, upon which Charleston is built, was originally an irregular tract of comparatively high and dry land, invaded at many points of its boundary by inlets of low swampy ground or salt marsh. These inlets, as the city grew, were gradually filled up so as to be on about the same level as the higher ground. * * * As a general rule, though not without a considerable number of exceptions, the destruction was greater upon made ground than upon the original higher land. [p. 248–249] * * *

In truth, there was no street in Charleston which did not receive injuries more or less similar to those just described. To mention them in detail would be wearisome and to no purpose. The general nature of the destruction may be summed up in comparatively few words. The destruction was not of that sweeping and unmitigated order which has befallen other cities, and in which every structure built of material other than wood has been either leveled completely to the earth in a chaos of broken rubble, beams, tiles, and planking, or left in a condition practically no better. On the contrary, a great majority of houses were left in a condition shattered indeed, but still susceptible of being repaired. Undoubtedly there were very many which, if they alone had suffered, would never have been repaired at all, but would have been torn down and new structures built in their places; for no man likes to occupy a place of business which suffers by contrast with those of his equals. But when a common calamity falls upon all, and by its very magnitude and universality renders it difficult to procure the means of reconstruction, and where thousands suffer much alike, his action will be different. Thus a very large number of buildings were repaired which, if the injuries to them had been exceptional misfortunes instead of part of a common disaster, would have been replaced by new structures. Instances of total demolition were not common.

This is probably due, in some measure, to the stronger and more enduring character of the buildings in comparison with the rubble and adobe work of those cities and villages which are famous chiefly for the calamities which have befallen them. Still the fact remains that the violence of the quaking at Charleston, as indicated by the havoc wrought, was decidely less than that which has brought ruin to other localities. The number of houses which escaped very serious injuries to their walls was rather large; but few are known to have escaped minor damages, such as small cracks, the loss of plastering, and broken chimney tops. [p. 253]

Damage to the three railroad tracks that extend north, northwest, and southwest from Charleston began about 6 km (3.7 mi) northwest of the city and was extensive (fig. 1*A*). More than 80 km (62 mi) of these tracks was affected. The effects listed were: lateral and vertical displacement, formation of S-shaped curves, and the longitudinal movement of hundreds of meters of track. A detailed listing of the effects along the South Carolina Railroad tracks, which run northwest from Charleston directly through the epicentral region, is given in table 1.

Ground cracks from which mud or sand are ejected and in which earthquake fountains or sand craters are formed begin on a small scale at intensity VIII, become notable at IX, and are large and spectacular phenomena at X (Richter, 1958, p. 139). The formation of sand craterlets and the ejection of sand were certainly widespread in the epicentral area of the 1886 earthquake. Many acres of ground were overflowed with sand, and craterlets as much as 6.4 m (21 ft) across were formed. Dutton (1889, p. 281) wrote: "Indeed, the fissuring of the ground within certain limits may be stated to have been universal, while the extravasation of water was confined to certain belts. The area within which these fissures may be said to have been a conspicuous and almost universal phenomenon may be roughly estimated at nearly 600 square miles [1,550 sq. km]." By comparison, the elliptical intensity-X contour suggested by the present study encloses an area of approximately 1,300 km^2.

The distribution of craterlets taken from Dutton (1889, pl. 28) is also shown in figure 1*A*. In a few localities, the water from the craters probably spouted to heights of 4.5–6 m (15–20 ft), as indicated by sand and mud on the limbs and foliage of trees overhanging the craters.

Other ground effects indicating the intensity-X level are fissures as much as a meter wide running parallel to canal and streambanks, and changes of

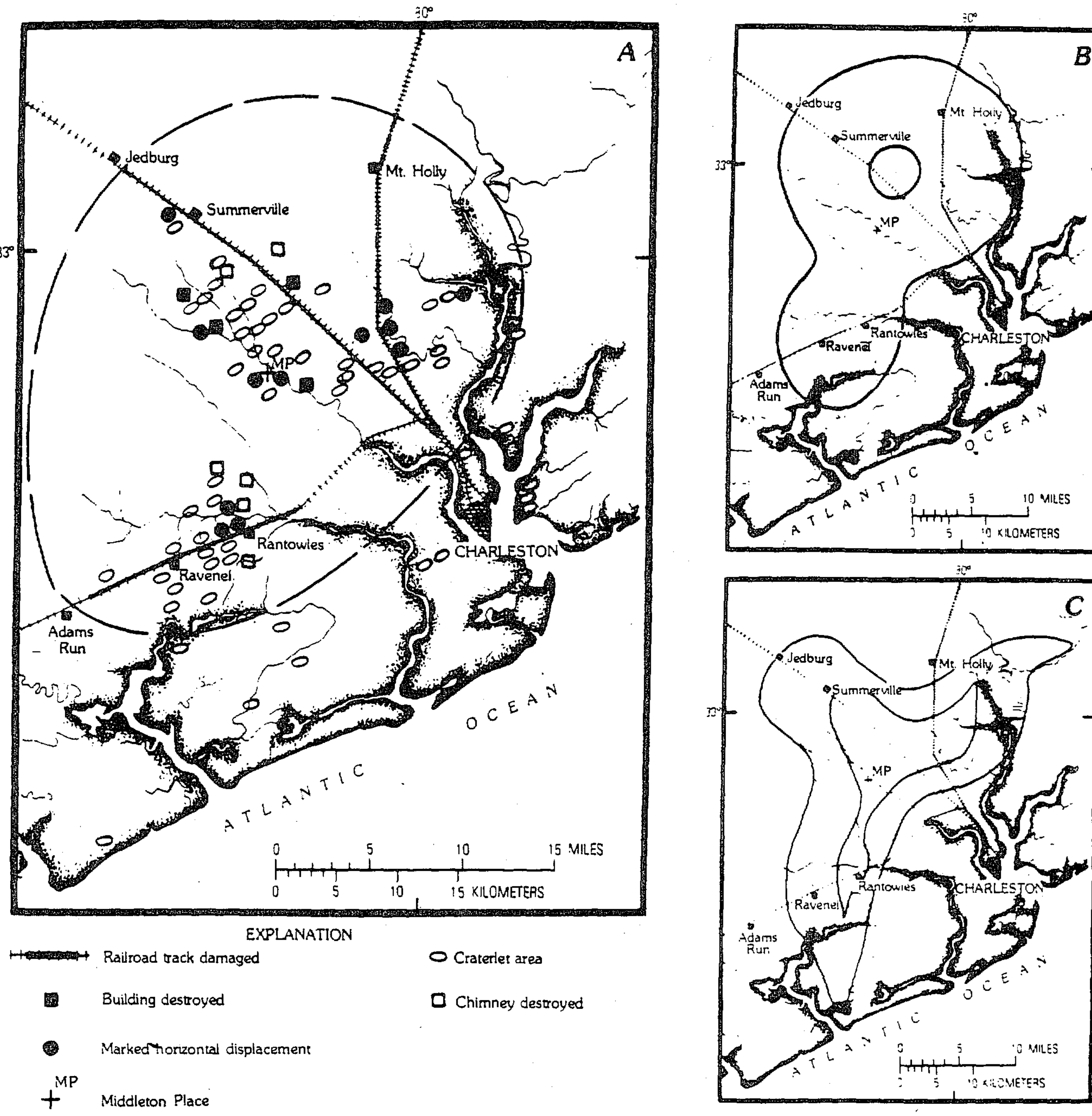

Figure 1.—Epicentral area maps for the 1886 Charleston, S.C., earthquake. *A*, This study. Dashed contour encloses intensity-X effects. *B*, Dutton's map and *C*, Sloan's map (modified from Dutton, 1889, pls. 26 and 27, respectively) show contours enclosing the highest intensity zone, although neither Dutton nor Sloan labeled his contours. Base map modified from Dutton (1889). Rivers flowing past the Charleston peninsula are the Ashley River flowing from the northwest and the Cooper River flowing from the north.

the water level in wells (Wood and Neuman, 1931). Dutton (1889, p. 298) reported that a series of wide cracks opened parallel to the Ashley River (see caption, fig. 1) and that the sliding of the bank riverward uprooted several large trees, which fell over into the water. His plate 23 shows a crack along the bank of the Ashley River about a meter wide and some tens of meters long across the field of view of the photograph.

In a belt of craterlets (trend N. 80° E., length ~5 km) about 10 km (6.2 mi) southeast of Summerville, Sloan reported (Dutton, 1889, p. 297) that

TABLE 1.—*Variation of intensity effects along the South Carolina Railroad*

[Based on Dutton, 1889, p. 282–287. Refer to fig. 1 for locations mentioned]

Distance from Charleston (km)	Distance from Charleston (mi)	Effects
<5.8	<3.66	Occasional cracks in ground; no marked disturbance of track or roadbed.
5.8	3.66	Rails notably bent and joints between rail opened.
5.8–8	3.66–5	Ground cracks and small craterlets.
8	5	Fishplates torn from fastenings by shearing of the bolts; joints between rails opened to 17.5 cm (7 in.).
9.6	6	Joints opened, roadbed permanently depressed 15 cm (6 in.).
14.4	9	Lateral displacements of the track more frequent and greater in amount; serious flexure in the track that caused a train to derail; more and larger craterlets.
16	10	Craterlets seemed to be greater in size (as much as 6.4 m (21 ft) across) and number; many acres overflowed with sand.
16–17.6	10–11	Maximum distortions and dislocations of the track; often displaced laterally and sometimes alternately depressed and elevated; occasional severe lateral flexures of double curvature and great amount; many hundreds of meters of track shoved bodily to the southeast; track parted longitudinally, leaving gaps of 17.5 cm (7 in.) between rail ends; 46 cm (18 in.) depression or sink in roadbed over a 18-m (60-ft) length.
17.6–24	11–15	Many lateral deflections of the rails.
24–25.6	15–16	Epicentral area—a few wooden sheds with brick chimneys completely collapsed; railroad alinement distorted by flexures; elevations and depressions, some of considerable amount, also produced.
29–30.6	18.5–19	Flexures in track, one in an 8.8-m (29-ft) section of single rails had an S-shape and more than 30 cm (12 in.) of distortion.
32	≈20	". . . a still more complex flexure was found. Beneath it was a culvert which had been strained to the northwest and broken" (p. 286); a long stretch of the roadbed and track distorted by many sinuous flexures of small amplitude.
33.9	21	Tracks distorted laterally and vertically for a considerable distance.
34.9	21.66	At Summerville—many flexures, one of which was a sharp S-shape; broken culvert under tracks in a sharp double curvature.
35.4–44.3	22–27.5	Disturbance to track and roadbed diminishes rapidly.
44.3	27.5	At Jedburg—a severe buckling of the track.

wells had been cracked in vertical planes from top to bottom, and that the wells had been almost universally disturbed, many overflowing and subsequently subsiding, others filling with sand or becoming muddy.

In Summerville, whose population at that time was about 2,000, the structures were supported on wood posts or brick piers 1–2 m high and, though especially susceptible to horizontal motions, the great majority did not fall. Rather, the posts and piers were driven into the soil so that many houses settled in an inclined position or were displaced as much as 5 cm. Chimneys, which were constructed to be independent of the houses, generally had the part above the roofline dislodged and thrown to the ground. Below the roofs, many chimneys were crushed at their bases, both bricks and mortar being disintegrated and shattered, allowing the whole column to sink down through the floors. This absence of overturning in piered structures plus the nature of the damage to chimneys was interpreted by Dutton as evidence for predominantly vertical ground motions.

The preceding discussion indicates an intensity-X level of shaking in the epicentral area. Figure 1*A* depicts the approximate extent of this region along with the locations of rail damage, craterlet areas, building damage, and areas of marked horizontal displacements. Dutton and his coworkers did not map the regions of pronounced vertical-motion effects, but they did emphasize the importance of these effects in the epicentral region. Also shown in figure 1 (*B* and *C*) is the extent of the highest intensity zone, as given by Dutton and by Sloan. Because of the sparsely settled and swampy nature of the region, the meizoseismal area cannot be defined accurately.

INTENSITY EFFECTS THROUGHOUT THE COUNTRY

Dutton (1889) published all his intensity reports, some 1,337, but he did not list the intensity values that he assigned to each report, nor did he show the location of the data points on his isoseismal map. By using the basic data at hand, a reevaluation was attempted to present another interpretation of the data (in the MM scale) and to determine whether additional information could be extracted concerning this important earthquake. The writer and two other seismologists (Rutlage Brazee, N.O.A.A., and Ruth Simon, U.S.G.S.) each independently evaluated Dutton's intensity data listing according to the MM scale. For the resulting 1,047 usable reports, ranging from MM level I to X, at least two of the three interpreters agreed on intensity values for 90 percent of the reports. As would be expected, most of the disagreement was found at the lower intensity levels (II–V). A full listing of the three independent intensity assignments for each location was made by Bollinger and Stover (1976).

The consensus values, or the average intensity values, in the 10 percent of the reports where all three interpreters disagreed were plotted at two different map scales and contoured (figs. 2–5). When multiple reports were involved, for example, those from cities, the highest of the intensity values obtained was assigned as the value for that location.

The greatest number of reports (178) for an individual State was from South Carolina. Figure 2 presents the writer's interpretation of these data. Even

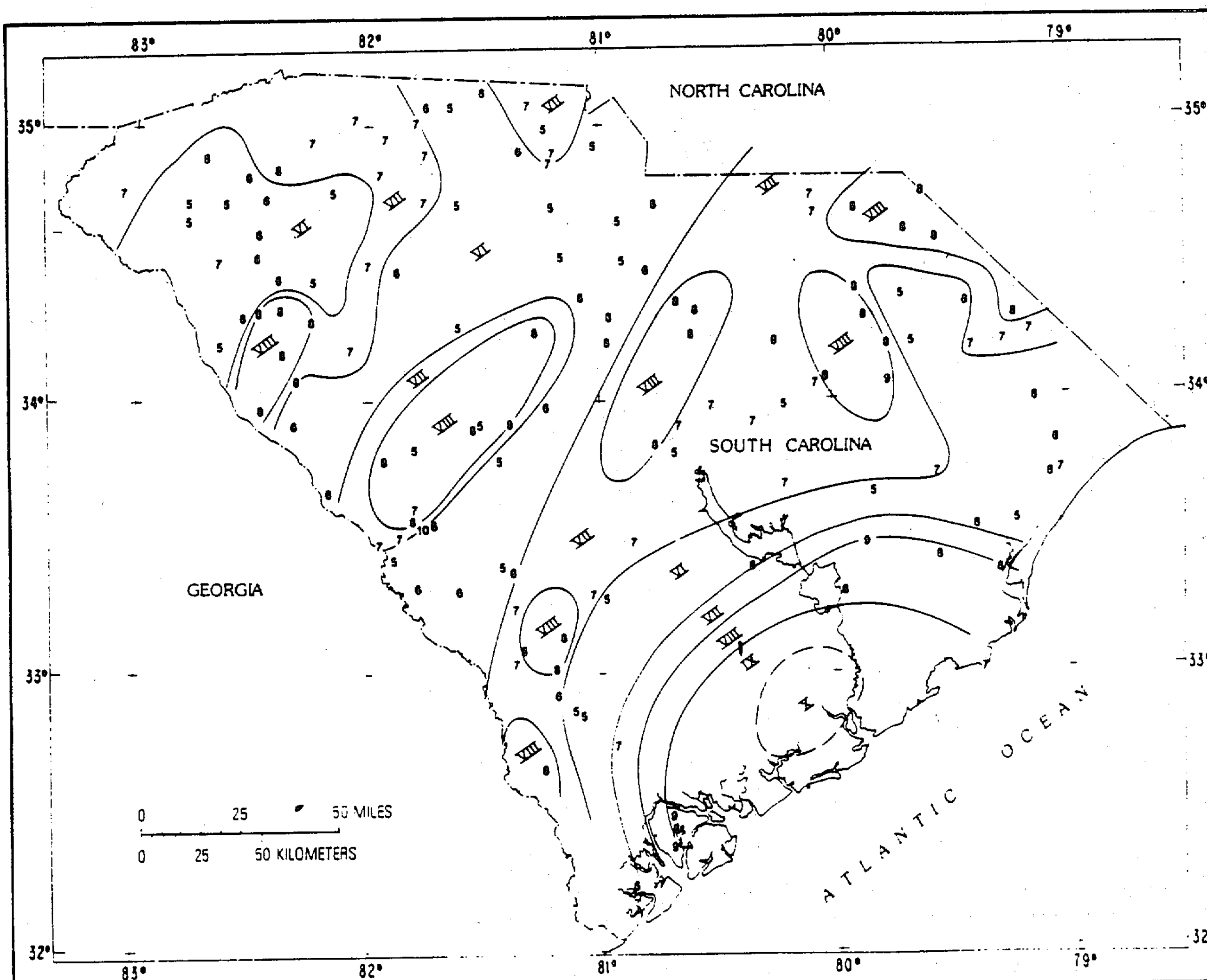

FIGURE 2.—Isoseismal map showing the State of South Carolina for the 1886 Charleston earthquake. Intensity observations are indicated by Arabic numerals, and the contoured levels are shown by Roman numerals.

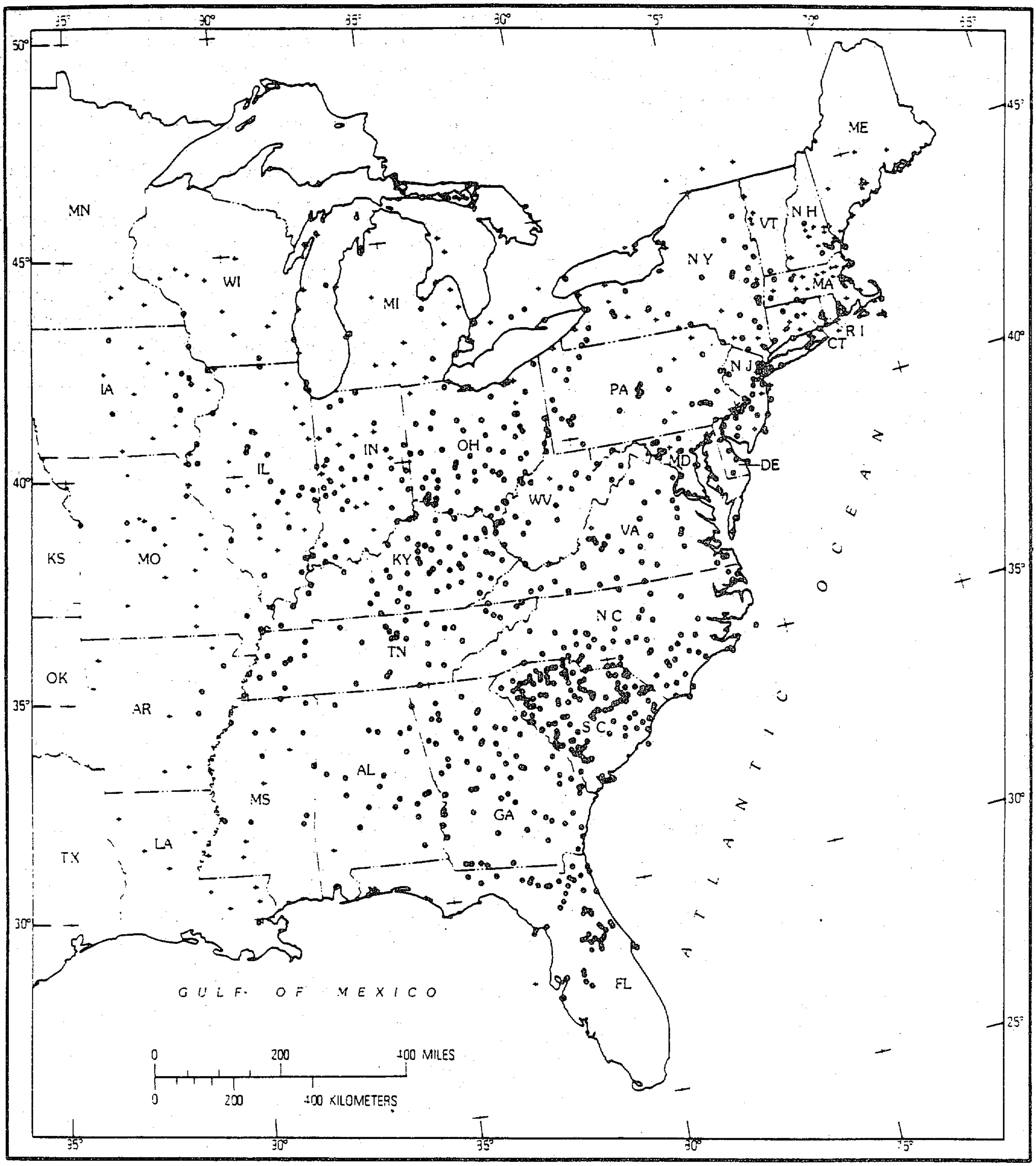

FIGURE 3.—Eastern United States showing the distribution of intensity observations for the 1886 Charleston earthquake. Solid circles indicate felt reports; small crosses indicate not-felt reports.

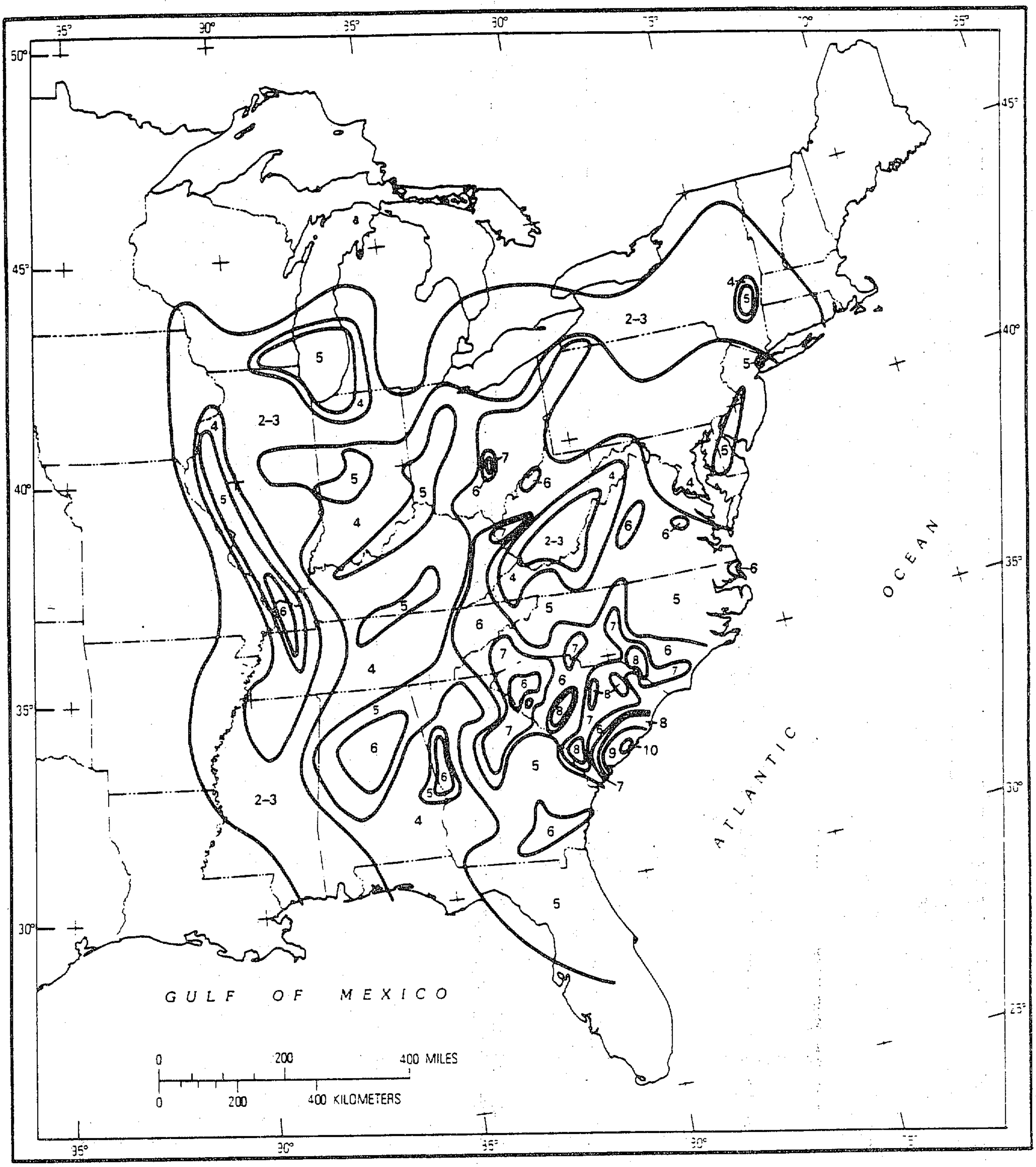

FIGURE 4.—Isoseismal map of the Eastern United States contoured to show the more localized variations in the reported intensities for the 1886 Charleston earthquake. Contoured intensity levels are shown by Arabic numerals.

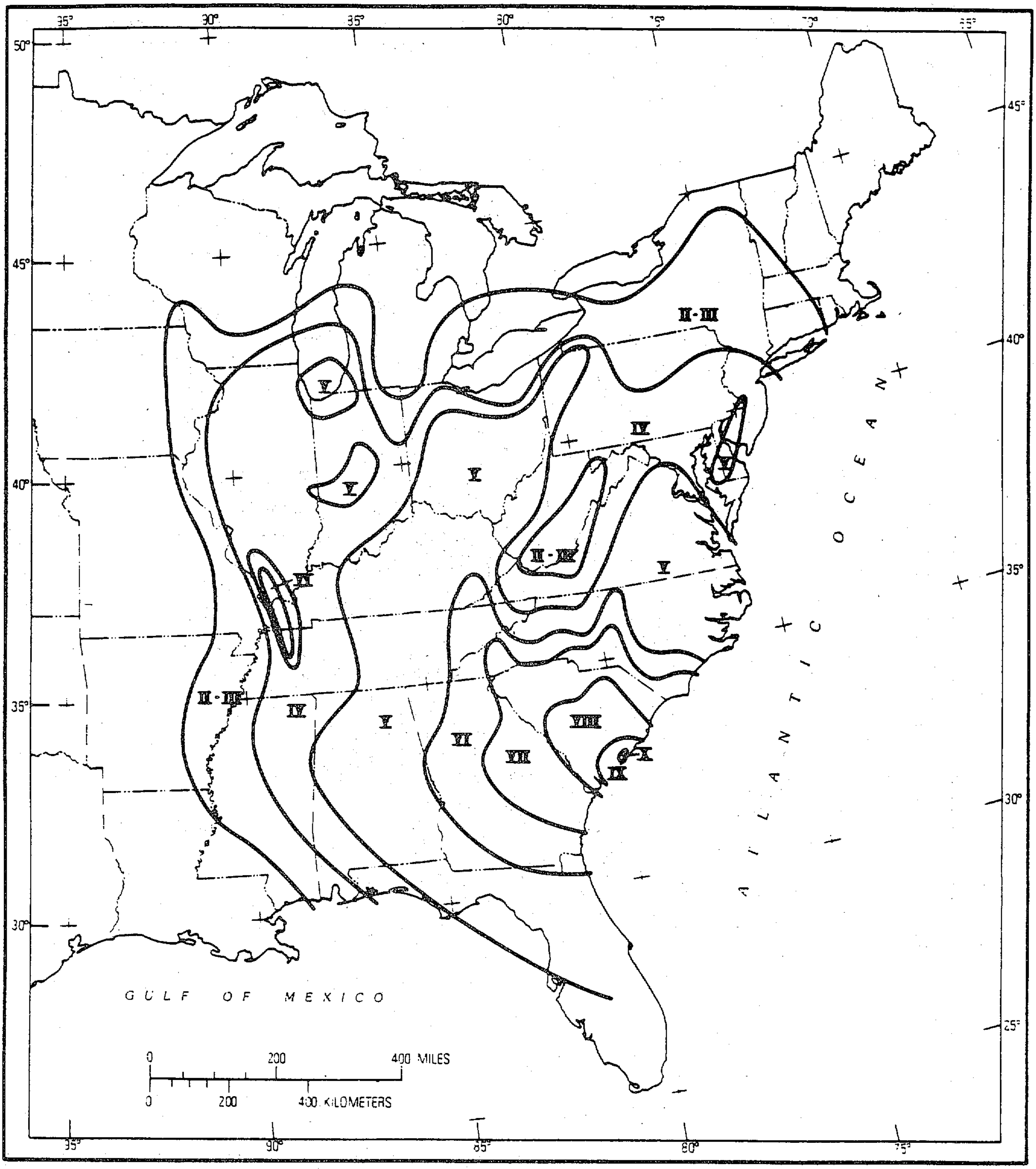

FIGURE 5.—Isoseismal map of the Eastern United States contoured to show the broad regional patterns of the reported intensities for the 1886 Charleston earthquake. Contoured intensity levels are shown in Roman numerals.

in contouring the mode of the intensity values, as was done here, intensity effects vary considerably with epicentral distance within the State. In particular, two intensity-VI zones are shown that trend northeastward across the State and separate areas of intensity-VIII effects. Although some of this variation may be due to incomplete reporting and (or) population density, it seems more likely that the local effects of surficial geology, soils, and water-table level are being seen. Interpreted literally, a very complex behavior of intensity is seen in the epicentral region.

The intensity data base and interpretive, isoseismal lines throughout the Eastern United States are shown in figures 3–5. In figure 4, the data are contoured to emphasize local variations, whereas figure 5 depicts the broad regional pattern of effects. Richter (1958, p. 142–145), in discussing the problem of how to allow for or represent the effect of ground in drawing isoseismal lines, suggested that two isoseismal maps might be prepared. One map would show the actual observed intensities; the other map would show intensities inferred for typical or average ground. The procedure followed here was to contour the mode of the intensity values (figs. 2 and 4) so as to portray the observed intensities in a manner that emphasizes local variations. Those isoseismal lines were then subjectively smoothed to produce a second isoseismal map showing the regional pattern of effects (fig. 5). The two maps that result from this procedure seem to the writer to represent reasonable extremes in the interpretation of intensity data. The subjectivity always involved in the contouring of intensity data is well known to workers concerned with such efforts. The purpose of the dual presentation here is to emphasize this subjectivity and to point out that, depending on the application, one form may be more useful than the other. Both local and regional contouring interpretations are to be found in the literature for U.S. earthquakes.

Figures 4 and 5 show that a rather complex isoseismal pattern, including Dutton's low-intensity zone (epicentral distance = $\Delta \cong 550$ km (341 mi)) in West Virginia, was present outside South Carolina. Intensity-VIII effects were observed at distances of 250 km (150 mi) and intensity-VI effects were observed 1,000 km (620 mi) from Charleston. Individual reports, given below, are all paraphrased from Dutton (1889). They note what took place in areas affected by intensity VI (MM) or higher at epicentral distances greater than about 600 km (372 mi). Some of these reports were ignored in the contouring shown in figure 4.

Intensity VI–VIII in Virginia ($\Delta \cong 600$ km (372 mi)):

Richmond (VIII)—Western part of the city: bricks shaken from houses, plaster and chimneys thrown down, entire population in streets, people thrown from their feet; in other parts of the city, earthquake not generally felt on ground floors, but upper floors considerably shaken.

Charlottesville (VII)—Report that several chimneys were overthrown.

Ashcake (VI)—Piano and beds moved 15 cm (6 in.); everything loose moved.

Danville (VI)—Bricks fell from chimneys, walls cracked, loose objects thrown down, a chandelier swung for 8 minutes after shocks.

Lynchburg (VI)—Bricks thrown from chimneys, walls cracked in several houses.

Intensity VII in eastern Kentucky and western West Virginia ($\Delta \cong 650$ km (404 mi)):

Ashland, Ky. (VIII)—Town fearfully shaken, several houses thrown down, three or four persons injured.

Charleston, W. Va.—"A number of chimneys toppled over" (p. 522).

Mouth of Pigeon, W. Va.—Chimneys toppled off to level of roofs, lamps broken, a house swayed violently.

Intensity VI in central Alabama ($\Delta \cong 700$ km (434 mi)):

Clanton (VII)—Water level rose in wells, some went dry and others flowed freely; plastering ruined.

Cullman—House wall cracked, lamp on table thrown over.

Gadsden—People ran from houses.

Tuscaloosa—Walls cracked, chimneys rocked, blinds shaken off, screaming women and children left houses.

Intensity VII in central Ohio ($\Delta \cong 800$ km (496 mi)):

Lancaster—Several chimneys toppled over, decorations shaken down, hundreds rushed to the streets.

Logan—Bricks knocked from chimney tops, houses shaken and rocked.

Intensity VI in southeastern Indiana and northern Kentucky ($\Delta \cong 800$ km (496 mi)):

Rising Sun, Ind.—Plaster dislodged, ornaments thrown down, glass broken.

Stanford, Ky.—Some plaster thrown down, hanging lamps swung 15 cm (6 in.).

Intensity VI in southern Illinois, eastern Tennessee, and Kentucky (Δ≅950 km (590 mi)):

Cairo, Ill.—Broken windows, "houses settled considerably" (p. 430) in one section, ceiling cracked in post office.

Murphysboro, Ill.—Brick walls shook, firebell rang for a minute, suspended objects swung.

Milan, Tenn.—Cracked plaster, people sitting in chairs knocked over.

Clinton, Ky.—Some bricks fell from chimneys.

Intensity VI in central and western Indiana (Δ≅1,000 km (620 mi)):

Indianapolis—Earthquake not felt on ground floors; part of a cornice displaced on one hotel, people prevented from writing at desks, clock in court house tower stopped, a lamp thrown from a mantle.

Terre Haute—Plaster dislodged, sleepers awakened; in Opera House, earthquake felt by a few on the ground floor, but swaying caused a panic in the upper galleries.

Madison—Several walls cracked, chandeliers swung.

Intensity VI in northern Illinois and Indiana (Δ≅1,200 km (744 mi)):

Chicago, Ill.—Plaster shaken from walls and ceilings in one building above the fourth floor; barometer at Signal Office "stood 0.01 inches higher than before the shock for eight minutes" (p. 432); earthquake not felt in some parts of City Hall, especially noticeable in upper stories of tall buildings, not felt on streets and lower floors.

Valparaiso, Ind.—Plaster thrown down in hotel, chandeliers swung, windows cracked, pictures thrown from walls.

The preceding reports indicate that structural damage extended to epicentral distances of several hundred kilometers and that apparent long-period effects were present at distances exceeding 1,000 km (620 mi). Persons also frequently reported nausea at these greater distances.

Dutton apparently contoured his isoseismal map in a generalized manner, which is an entirely valid procedure. The rationale in that approach is to depict not the more local variations, as was presented in the above discussion, but rather the regional pattern of effects from the event. Figure 5 is the writer's attempt at that type of interpretation, and the resulting map is very similar to Dutton's.

ATTENUATION OF INTENSITY WITH EPICENTRAL DISTANCE

The decrease of intensity with epicentral distance is influenced by such a multiplicity of factors that it is particularly difficult to measure. The initial task in any attenuation study is to specify the distance (or distance range) associated with a given intensity level. Common selections are: minimum, maximum, or average isoseismal contour distances or the radius of an equivalent area circle. In all these approaches, the original individual intensities are not considered; rather, isoseismal maps are used. Perhaps a better, but more laborious, procedure has been suggested by Perkins (oral commun., 1975), wherein the intensity distribution of observations is plotted for specific distance intervals. In this manner, all the basic data are presented to the reader without interpretation by contouring. He is then in a position to know exactly how the data base is handled and thereby to judge more effectively the results that follow. Once the intensity-distance data are cast in this format, they are then also available for use in different applications.

The epicentral distances to some 800 different locations affected by the 1886 shock were measured and are listed in table 2. For these measurements, the center of the intensity X (fig. 1) area was assumed to be the epicenter. Figure 6 presents the resulting intensity distributions as functions of epicentral distance. The complexity present in the isoseismal maps (figs. 4 and 5) is now transformed to specific distances, and the difficulty of assigning a single distance or distance interval to a given intensity level is clearly shown. The approach followed here was to perform a regression analysis on the intensity-distance data set, using an equation of the form,

TABLE 2.—*Number of intensity observations as a function of epicentral distance intervals for the 1886 Charleston, S. C., earthquake*

Epicentral distance (km)	IX	VIII	VII	VI	V	IV	II–III	Number of observations
50– 99	3	4	3	3	3	---	---	16
100– 199	2	18	18	17	18	1	---	74
200– 299	-	9	22	25	30	5	---	91
300– 399	-	3	16	12	31	8	---	70
400– 499	-	2	3	10	26	19	12	72
500– 599	-	1	3	11	13	19	7	54
600– 699	-	1	3	3	14	33	11	65
700– 799	-	--	3	4	22	16	22	67
800– 899	-	--	1	2	29	20	20	72
900– 999	-	--	--	3	18	17	30	68
1,000–1,249	-	--	--	4	24	19	48	95
1,250–1,499	-	--	--	--	6	6	20	32
1,500–1,749	-	--	--	--	---	1	3	4
Totals	5	38	72	94	234	164	173	780

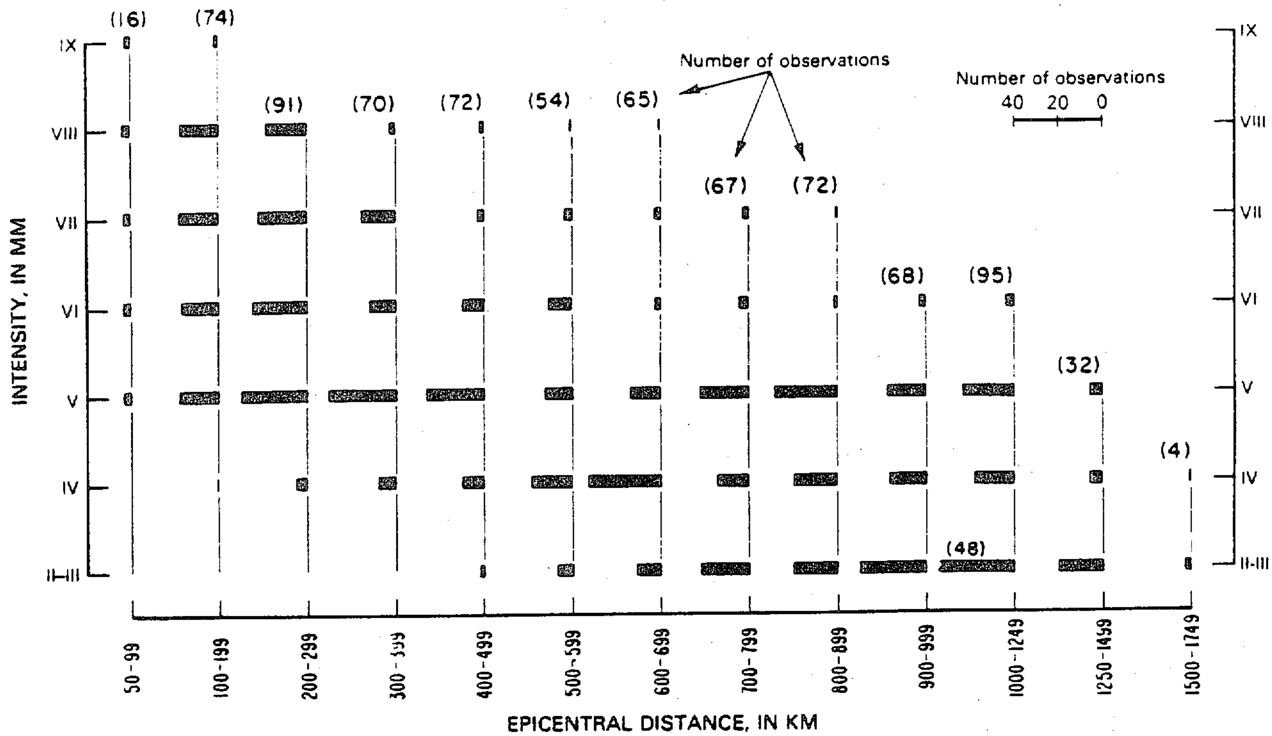

FIGURE 6.—Distribution of intensity (Modified Mercalli, MM) as a function of epicentral distance (km) for the 1886 Charleston earthquake. Intensity distribution is shown for specific distance intervals.

$$I = I_0 + a + b\Delta + c \log \Delta,$$

where a, b, c are constants, Δ is the epicentral distance in kilometers, I_0 is the epicentral intensity, and I is the intensity at distance Δ. This equation form was selected because it has been found useful by other investigators (for example, Gupta and Nuttli, 1976). The resulting fit for the median, or 50-percent fractile, was,

$$I = I_0 + 2.87 - 0.00052\Delta - 2.88 \log \Delta.$$

The standard deviation, σ_I, between the observed and predicted intensities, is 1.2 intensity units for these data. For the 75-percent fractile, the a constant is 3.68; for the 90-percent fractile, the a constant is 4.39. The b term is very small and could perhaps be deleted, as it results in only half an intensity unit at 1,000 km. The minimum epicentral distance at which the equation is valid is probably 10–20 km. The intensity-distance pairs extend to within only 50 km of the center of the epicentral region, but that region (fig. 1) has a diameter of approximately 20 km.

The curves for the 50-, 75-, and 90-percent fractiles are shown in figures 7 and 8 along with other published intensity attenuation curves for the Central and Eastern United States. Isoseismal maps

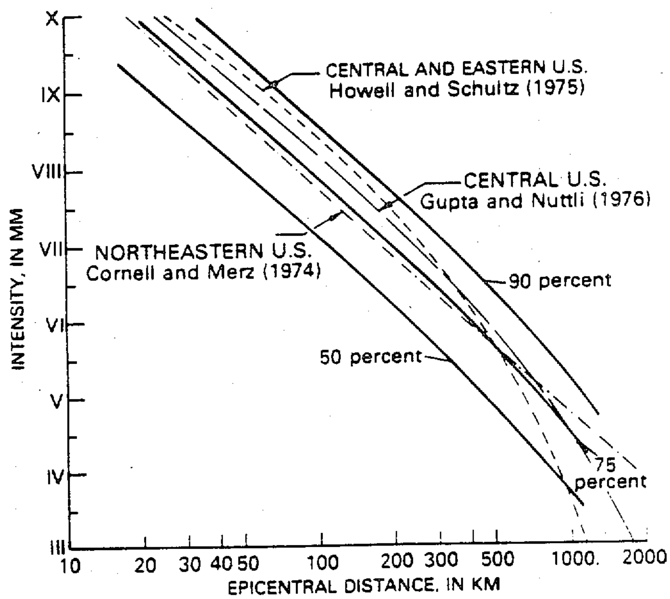

FIGURE 7.—Attenuation of intensity (MM) with epicentral distance (km) for various fractiles of intensity at given distance intervals for the 1886 Charleston earthquake (heavy solid curves). Attenuation functions by Howell and Schultz (1975), Gupta and Nuttli (1976), and Cornell and Merz (1974) are shown by light dashed curves.

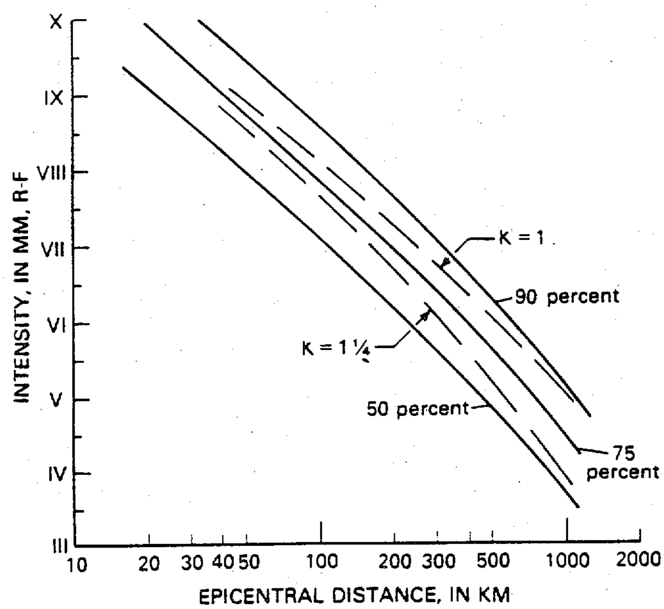

FIGURE 8.—Attenuation of intensity (MM) with epicentral distance (km) for various fractiles of intensity at given distance intervals for the Charleston earthquake (solid curves). Evernden's attenuation curves (1975) (Rossi-Forel intensity scale; L=10 km, C=25 km, k=1 and 1¼) are shown by dashed curves for I_0=X.

were utilized to develop these latter curves, and the general agreement between the entire suite of curves is remarkable. A direct comparison between curves, which may not be valid because of different data sets and different regions, would suggest that the Howell and Schultz (1975) curve is at about the 85-percent fractile, the Gupta and Nuttli (1976) curve is at the 80-percent fractile, and the Cornell and Merz (1974) curve is at the 70-percent fractile. At the intensity-VI level and higher, note that there is less than one intensity-unit difference among the Central United States, Central and Eastern United States, and Northeastern United States curves and the 75- and 90-percent fractile curves of this study.

Evernden's (1975) curves (fig. 8) for his k=1 and k=1¼ factors lie between the 50- and 90-percent fractile curves of this study. Evernden used k factors to describe the different patterns of intensity decay with distance in the United States. A value of k=1¼ was found for the Gulf and Atlantic Coastal Plains and the Mississippi Embayment and a k=1 for the remainder of the Eastern United States. Evernden prefers to work with the Rossi-Forel (R-F) intensity scale. The difference between the R-F and MM scales is generally about half an intensity unit, and conversion to R-F values would essentially result in translating the fractile curves of this study upward by that amount. This would put the 75-percent fractile curve in near superposition with Evernden's k=1 curve. Such a result is perhaps not surprising because approximately two-thirds of the felt area from the 1886 shock is in Evernden's k=1 region, and isoseismal lines are often drawn to enclose most of the values at a given intensity level. Although differences in intensity attenuation may exist between various parts of the Eastern United States, it would appear from this study that the dispersion of the data (σ_I=1.2) could preclude its precise definition. If, indeed, significant differences do exist between the various regions, then the curves given here would apply to large shocks in the Coastal Plain province of the Southeastern United States.

The advantages of the method presented herein are that it allows a prior selection of the fractile of the intensity observations to be considered and that it eliminates one subjective step, the contouring interpretation of the intensity data. Furthermore, the dispersion of the intensity values can be calculated.

Neumann (1954) also presented intensity-versus-distance data in a manner similar to that described above. However, Neumann did not consider the intensity distribution for specific distance intervals as was done herein, but rather plotted the distance distribution for each intensity level. To illustrate the difference in the two approaches, the 1886 earthquake data were cast in Neumann's format (fig. 9).

MAGNITUDE ESTIMATE

Nuttli (1973), in arriving at magnitude estimates for the major shocks in the 1811–1812 Mississippi Valley earthquake sequence, developed a technique for correlating isoseismal maps and instrumental ground-motion data. Later, he (1976) presented specific amplitude-period $(A/T)_z$ values for MM intensities IV through X for the 3-second Rayleigh wave. Basically, Nuttli's technique consists of:

(1) Determination of a relation between $(A/T)_z$ and intensity from instrumental data and isoseismal maps,

(2) Use of the $(A/T)_z$ level at 10-km epicentral distance derived from the m_b value for the largest well-recorded earthquake in the region. That level will serve as a reference level from which to scale other m_b magnitudes,

(3) For the historical event of interest, assign epicentral distances (Δ) to each intensity level from the isoseismal map for the event. Convert from intensity to $(A/T)_z$, according to the relationship of (1) above, then

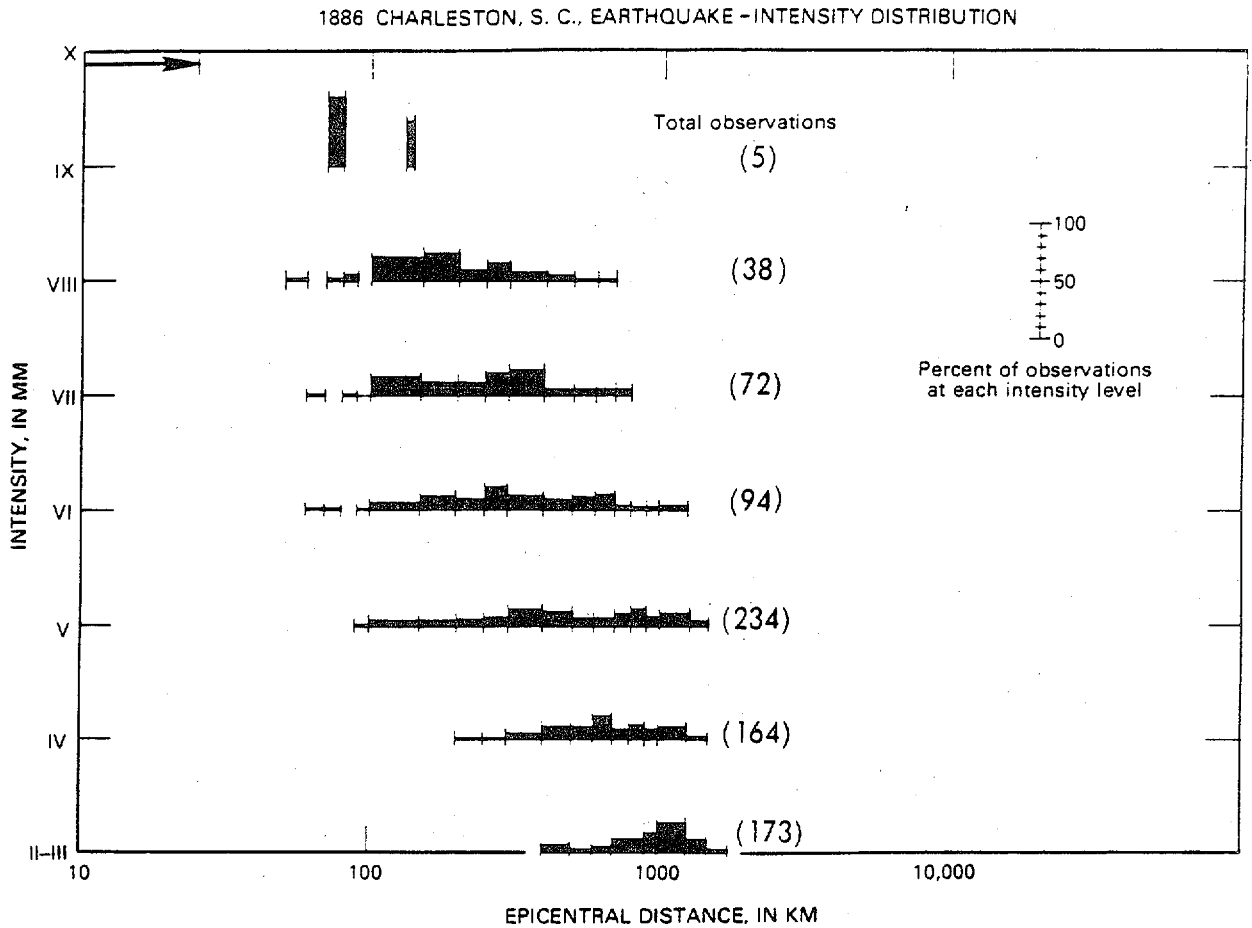

Figure 9.—Distribution of epicentral distances (km) for given intensity (MM) levels of the 1886 Charleston earthquake.

(4) Plot $(A/T)_z$ versus Δ and fit with a theoretical attenuation curve. Next, scale from (2) above to determine the Δm_b between the historical shock and the reference earthquake.

In the $(A/T)_z$ versus intensity of (1) and the curve fitting of (4), Nuttli found that surface waves having periods of about 3 seconds (s) were implied. He justified the use of m_b (determined from waves having periods of about 1 s) by assuming that the corner periods of the source spectra of the earthquakes involved are no less than 3 s. This implies a constant proportion between the 1- and 3-s energy in the source spectra. Nuttli used m_b rather than M_s because he felt that, for his reference earthquake, the former parameter was the more accurately determined.

If we apply Nuttli's technique to the 1886 earthquake and use the distances associated with the 90-percent fractile intensity-distance relationship, the resulting m_b estimate is 6.8 (fig. 10). Nuttli (1976) obtained a value of 6.5 when he used Dutton's isoseismal map and converted from the Rossi-Forel scale to the MM scale. If the Trifunac and Brady (1975) peak velocity versus MM intensity relationship, derived from Western United States data, is taken with the 90-percent fractile distances, then the m_b estimate is 7.1 (fig. 10). Because the 90-percent fractile curve is the most conservative, it results in the largest intensity estimate at a given distance. The magnitude estimates in this study would be upper-bound values.

My magnitude estimates, as well as those of Nuttli, are based primarily on three previously mentioned factors: intensity-distance relations, intensity-particle velocity relations, and reference magnitude level (or, equivalently, the reference earthquake, which in this instance is the November 9, 1968, Illinois earthquake with m_b=5.5). In the Central and Eastern United States, the data base for the later two factors is very small. It is in this context that the magnitude estimates should be considered.

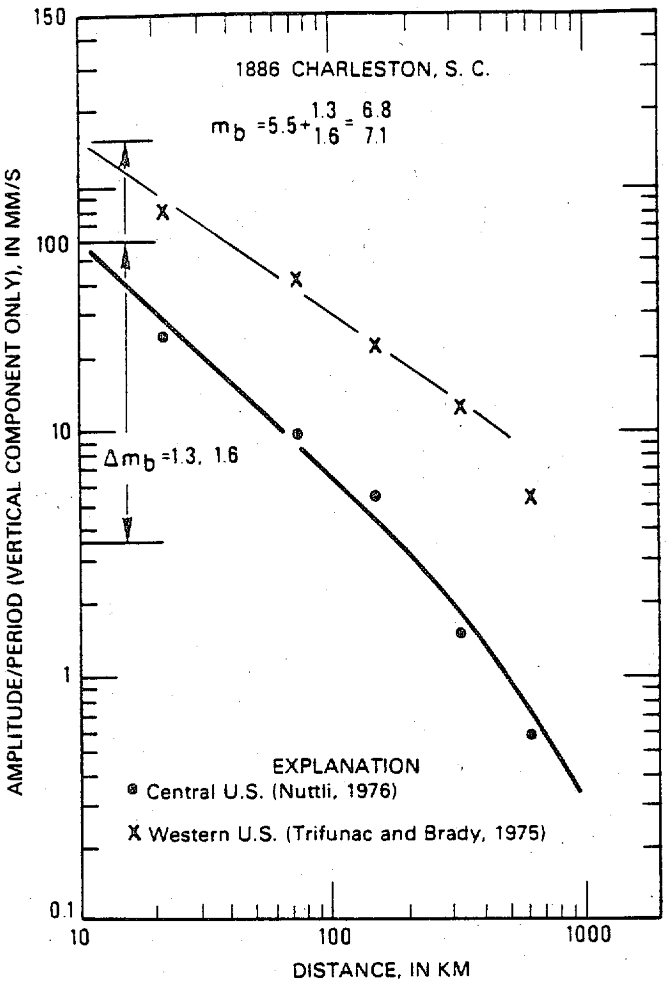

FIGURE 10.—Body wave magnitude (m_b) estimates for the 1886 Charleston earthquake based on Nuttli's (1973, 1976) technique. Nuttli's Central United States particle velocity-intensity data are indicated by solid circles. Trifunac and Brady's (1975) Western United States particle velocity-intensity data are indicated by X's. Distances are from the 90-percent fractile curve of this study. Heavy curve is Nuttli's (1973) theoretical attenuation for the 3-s Rayleigh wave. Western United States data fit with a straight line (light curve).

CONCLUSIONS

The intensity data base published by Dutton (1889) has been studied, and the principal results of that effort are as follows:

1. The maximum epicentral intensity was X (MM), and the intensity in the city of Charleston was IX (MM).
2. The writer verified that Dutton's isoseismal map was contoured so as to depict the broad regional pattern of the effects from ground shaking.
3. When contoured to show more localized variations, the intensity patterns show considerable complexity at all distances.
4. The epicentral distance was measured to each intensity observation point and the resulting data set (780 pairs) was subjected to regression analysis. For the 50-percent fractile of that data set, the equation developed was

$$I = I_0 + 2.87 - 0.00052\Delta - 2.88 \log \Delta$$

with a standard deviation (σ_I) of 1.2. For the 90- and 75-percent fractiles, the 2.87 constant is replaced by 4.39 and 3.68, respectively. This variation of intensity with distance agrees rather closely with relationships obtained by other workers for the central, eastern, and northeastern parts of the United States. It thus appears that the broad overall attenuation of intensities may be very similar throughout the entire Central and Eastern United States.

5. Using intensity-particle velocity data derived from Central United States earthquakes, the writer estimates a body-wave magnitude (m_b) of 6.8 for the main shock of August 31, 1886. However, the data base upon which this estimate is made is very small; therefore, the estimated m_b should be considered provisional until more data are forthcoming. Use of Western United States intensity-particle velocity data produces an m_b estimate of 7.1.

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